AN ALGORITHM TO REMOVE ANOMALOUS PROPAGATION CLUTTER RETURNS FROM ASR-9 WEATHER CHANNEL DATA USING PENCIL BEAM RADAR DATA

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1. Introduction*

The Integrated Terminal Weather System (ITWS), currently under development by the Federal Aviation Administration (FAA), will produce a fully automated, integrated terminal weather information system to improve the safety, efficiency and capacity of terminal area aviation operations. The ITWS will acquire data from FAA and National Weather Service sensors as well as from aircraft in flight in the terminal area. The ITWS will provide products to Air Traffic personnel that are immediately usable without further meteorological interpretation. These products include current terminal-area weather and short-term (0-30 minute) predictions of significant weather phenomena.

The ASR (Airport Surveillance Radar)-9 radar is used in the terminal area to control aircraft. This radar has a weather channel that provides the location and intensity of precipitation (6-level) on the air traffic controllers' radar screen. Controllers use the weather information to aid aircraft in avoiding weather. The ASR-9 radar data are often contaminated by anomalous propagation (AP). Due to the smoothing process used in the ASR-9, controllers are unable to distinguish between AP and valid weather returns. As a result controllers may attempt to vector aircraft around AP, resulting in increased controller workload and decreased terminal airspace capacity.

The ITWS product suite includes two precipitation products: ITWS Precipitation (AP removed) and the ASR-9 Precipitation (AP flagged in black). The basis for these products is the ASR-9 weather channel output. Both of these products are created by an algorithm called AP-edit.

The ITWS precipitation product is a representation of the location and intensity of precipitation in the TRACON (Terminal Radar Approach Control) area and may be used for situational awareness and as a planning aid for air traffic managers by showing where weather is located relative to traffic flow patterns. The ASR-9 precipitation product explicitly shows where AP clutter is located relative to any ASR-9 radar. Since the ITWS precipitation product does not replace the ASR-9 weather display on any controllers' displays, the Air Traffic Control (ATC) supervisor or traffic manager may use the ASR-9 precipitation product to indicate the location of AP clutter to any individual controller.

The products were demonstrated during the ITWS Demonstration and Validation Operational Test and Evaluation (OT&E) conducted at Memphis and Orlando International Airports during the summer of 1994. This paper describes the AP-edit algorithm and provides a preliminary evaluation of the performance of the algorithm.

2. ASR-9 Weather Channel

The ASR-9 radar is an S-band radar that transmits a 1-microsecond, 1-megawatt pulse. The width of the beam is 1.4 degrees in azimuth and greater than 5 degrees in elevation. The antenna rotation rate is about 12.5 RPM; thus, the radar completes a full 360-degree scan in about 5 seconds. The primary purpose of this radar is to detect aircraft from the surface to 20,000 feet.

In addition to aircraft detection capabilities, the ASR-9 can provide information on the location and intensity of precipitation in the TRACON area. The returned signal is passed through a filter that removes ground clutter. The data are smoothed in time over 6 antenna rotations which results in a 30-second update rate of the precipitation data. The data are also smoothed in space to a resolution of 1 km. During this smoothing process, the spatial extent of the highest intensity levels becomes exaggerated. The output is delivered in the standard National Weather Service 6-level (VIP) intensity scale.

3. Anomalous Propagation

The data from the ASR-9 weather channel are often contaminated by AP. In the standard atmosphere, a radar beam typically travels in a slightly curved path whose radius of curvature is greater than the earth's radius. Under superrefraction and ducting conditions, the path of the beam is more highly curved. Energy is diverted toward the ground and targets that would normally be below the radar horizon are illuminated. These ground clutter returns are often referred to as "anomalous propagation clutter." Because of the spatial and temporal smoothing performed by the ASR-9 weather channel processing, it is difficult for a user to look at a display and distinguish AP clutter from real weather signals.

The atmospheric conditions that cause AP are

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temperature inversions and moisture gradients. Under these conditions, the ASR-9 radar beam is bent downward and strikes the ground. During nocturnal inversions, the skies may be cloud-free but returns that look very similar to weather appear on the ASR-9 displays. As the inversion strengthens throughout the night, the AP increases in areal extent and intensity. This condition often causes the AP that users see in the late night to early morning hours.

In addition to the nocturnal inversion situation, the passage of a cold thunderstorm outflow over or near the ASR-9 site sets up an inversion condition that may cause AP. In this case, valid weather returns co-exist with, and may even be contaminated by, AP clutter. In the latter, the intensity of real weather appears to be greater than it actually is.

If the ASR-9 is so susceptible to AP contamination, why use it? The ASR-9 radar covers the primary area of interest to terminal ATC users (the TRACON), updates frequently (every 30 seconds), and the weather data are readily available to ATC users. The rapid update is essential in the context of controlling aircraft. The benefits gained from using the ASR-9 data outweigh the costs of removing AP.

4. Considerations in Removing AP Clutter from ASR-9 Data

Although the focus of the AP removal technique is to remove AP, precautions must be taken to insure that real weather returns are not "damaged." The presence of AP in an ATC product may cause a controller to vector aircraft unnecessarily, which has an economic impact (increased fuel usage, loss of airport capacity). However, decreasing or entirely removing valid weather returns from the product could result in a safety hazard. Therefore, any approach to removing AP must be very conservative.

Identification of AP is accomplished by comparing an ASR-9 cartesian image to the NEXRAD (Next Generation Weather Radar) Composite Maximum Reflectivity (comprefl) product. From this comparison, an AP mask is generated that isused to edit subsequent ASR-9 scans until a new comprefl is received.

The ASR-9 fan beam provides a near-instantaneous vertical integration of the weather. The comprefl represents the maximum reflectivity (in the column above a grid point) of the data collected over the duration of the volume scan. Because the ASR-9 update rate (30 seconds) is so much faster than the comprefl update rate (5 to 6 minutes), weather may develop and be detected by the ASR-9 before it appears in the comprefl product. For example, if rapid growth occurs below the NEXRAD beam, the NEXRAD may be scanning above the maximum reflectivity which would result in an underestimation of the maximum storm reflectivity by the comprefl product. In addition, gaps in the NEXRAD coverage may cause an underestimation of the reflectivity. While the NEXRAD is completing its volume scan, the ASR-9 is continuing to update every 30 seconds and will "see" the storm growth not captured by the NEXRAD comprefl. Thus, the potential exists for real weather in the ASR-9 to be wrongly identified as AP because there is not sufficient confirmation of the weather in the NEXRAD data.

There are two ways to guard against incorrect identification of weather as AP. The first way is to select for the comparison an ASR-9 scan that contains all possible weather returns present in the comprefl. This can be accomplished by using the ASR-9 scan (*i.e.*, the reference scan) that is produced closest to the beginning of the NEXRAD volume scan. That ASR-9 scan will not contain the weather that develops during the NEXRAD volume scan. On the other hand, AP increases in spatial extent and intensity in much the same way that weather does. AP that develops during the NEXRAD volume scan also is not present in the reference scan and AP breakthrough will occur. To **minimize the effect of rapid storm growth,** the reference scan should be the ASR-9 scan closest to the **beginning** of the NEXRAD volume scan. to **minimize AP breakthrough,** the refeence scan should be the ASR-9 scan closest to the **end** of the NEXRAD volume scan.

A second way to account for rapid growth is to choose editing parameters that explicitly guard against this possibility. It is assumed that the maximum growth rate of a storm is 30 dBZ per 5 minutes. (Henry, 1993 recorded growth from 10 dBZ to 40 dBZ in 8 minutes; Knight et. al, 1983 recorded growth from first cloud to 30 dBZ in 5 minutes in the presence of clouds. Growth rates close to these were computed for at least two of the storms documented by Meuse, *et al.* 1992) It is assumed further that rapid growth occurs at altitudes typical of the 0°C isotherm, about 5 km in Orlando. NEXRAD coverage to 7 km is required to insure that the growth region is scanned by the NEXRAD. Beyond 20 km, the NEXRAD scans to at least 7 km in altitude. Beyond about 100 km from the NEXRAD, the growth region is scanned in the first half of the NEXRAD precipitation volume scans. If growth occurs after the beam has passed the growth region, the NEXRAD comprefl product can underestimate maximum storm reflectivity. A growth rate of 6 dBZ per minute (*i.e.*, 30 dBZ in 5 minutes) over half of a volume scan (3 minutes) could result in an underestimate of maximum storm reflectivity of 18 dBZ. The editing parameters that result from these assumptions about storm growth rate are very stringent and adversely impact the ability to identify and remove AP. For example, a level 6 ASR-9 return could be confirmed as weather based on a 39 dBZ (level 2) NEXRAD return.

A combination of scan-timing selection and editing parameters can be used to 1) guard against rapid storm growth and 2) help reduce AP breakthrough. Using an ASR-9 scan closer to the **middle** of the NEXRAD volume scan allows one to relax the editing parameters while providing some protection against AP evolution.

5. Removing AP Clutter from ASR-9 Data

Weber, et. al (1993) described a method for filtering AP from an ASR-9 radar that was specially configured to

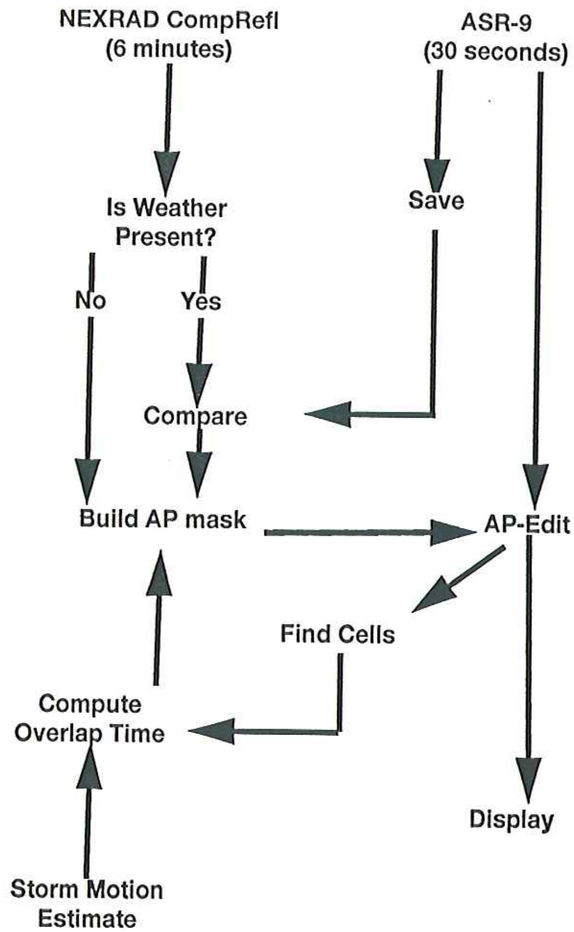

Figure 1. Schematic diagram of the AP-edit algorithm.

detect wind shear (ASR-WSP). This technique makes use of the fact that the Doppler velocity of AP clutter is nearly zero and that the spectrum width is very narrow. Unfortunately, the signal processing techniques developed for the ASR-WSP system require access to the Doppler data. For operational ASR-9 systems, the ITWS will not have access to the Doppler data, only to the 6-level smoothed data. Therefore, the "Weber approach" cannot be applied to operational ASR-9 radars as they are currently configured so a new AP-filtering technique was developed. The logic of the ITWS approach is illustrated in Figure 1.

An AP mask is created that contains information on the location of AP and the maximum allowable intensity (VIP level 1 through 6). The creation of the AP mask is initiated by the receipt of comprefl. When the comprefl is received, it is first searched to determine if any storms are present (*i.e.*, an attempt is made to identify the clear sky, nocturnal inversion case). If the search cannot identify at least 9** contiguous pixels (9 square kilometers) of reflectivity exceeding 17 dBZ**, a mask is created which, when applied to the ASR-9 data, causes all returns to be removed (*i.e.*, all values in the AP mask are set to BADVAL). All returns are removed from subsequent ASR-9 updates until a new comprefl is received and a new mask is created.

If the search of the comprefl indicates that weather reflectivity is present, a pixel-by-pixel (a pixel is 1 km^2) comparison is performed to determine if the ASR-9 data are contaminated by AP clutter. (AP-editing is not performed within the NEXRAD cone-of-silence [*i.e.*, 20 km of the NEXRAD] because the presence or absence of weather over the NEXRAD cannot be confirmed.) ASR-9 data collected at the middle** of the NEXRAD volume scan are compared to the comprefl to create the AP mask. For each ASR-9 pixel, an area 7 km x 7 km** centered on the ASR-9 pixel is searched. Each pixel in the mask is marked with the maximum acceptable weather level as determined from the rules provided in Table 1. For a given ASR-9 value (column 1), if the NEXARD search area does not contain at least 10** pixels of reflectivity above the corresponding threshold (column 2), the ASR-9 datum is assumed to be AP and the appropriate pixel value (column 3) for that ASR-9 datum is recorded in the AP mask. For example, if the ASR-9 pixel value is 5, at least 10 of the values in the NEXRAD search area must equal or exceed 37 dBZ for the ASR-9 pixel to be confirmed as VIP level 5. If the 10 NEXRAD values are greater than 27 dBZ, the ASR-9 datum will be reduced to VIP level 3.

The AP mask is used to edit the ASR-9 scan received immediately after the comprefl product and all subsequent ASR-9 scans until the receipt of a new comprefl. Only those grid points that are identified as containing AP in the original comparison are edited. Depending on the NEXRAD volume scan being used, the AP mask could as much as 9 minutes older than the ASR-9 data being edited.

Since weather moves (especially relative to the AP mask) the possibility exists that real weather will propagate into an area that was previously occupied by AP. Unless corrective action is taken, the valid weather returns would be edited in accordance with the AP mask. To account for motion, each edited ASR-9 scan is passed to a routine that finds cells of at least VIP level 3. Motion is estimated by a correlation tracking technique (Chornoboy, 1992; Chornoboy and Matlin, 1994) and assigned to each cell. From this, the time at which real weather is expected to overlap AP regions is computed. When the overlap time has expired, the pixel in the AP mask is "turned off" such that the ASR-9 return is passed through without change.

6. Technical Performance

There are basically three cases that must be considered when assessing the technical performance of the AP-edit algorithm: all AP, all weather, and mixed AP and weather. In the first case, all returns in the ASR-9 data are AP (*i.e.*, the clear sky, nocturnal inversion case). In the second case, all of the returns in the ASR-9 data are from real weather. In the third (and most stressful for the algorithm), AP and weather returns co-exist; AP can be

** This is a site adaptable parameter.

Table 1. Parameters for the AP-edit algorithm.

ASR-9 VIP Level	NEXRAD Value (dBZ)	AP Mask Value
6	≥ 42	6
6	≥ 37	5
6	≥ 32	4
6	≥ 27	3
6	≥ 22	2
6	≥ 17	1
6	< 17	BADVAL
5	≥ 37	5
5	≥ 32	4
5	≥ 27	3
5	≥ 22	2
5	≥ 17	1
5	< 17	BADVAL
4	≥ 32	4
4	≥ 27	3
4	≥ 22	2
4	≥ 17	1
4	< 17	BADVAL
3	≥ 27	3
3	≥ 22	2
3	≥ 17	1
3	< 17	BADVAL
2	≥ 22	2
2	≥ 17	1
2	< 17	BADVAL
1	≥ 17	1
1	< 17	BADVAL

unassociated with any valid weather returns (referred to as "clear air AP") and weather returns may be anomalously high due to contamination by AP. Although the performance metrics for each of the cases are the same, the performance of the algorithm with respect to these cases is generally considered independently in order to highlight the conditions under which the algorithm might fail.

Truth is generated by a human expert who compares raw ASR-9 data to NEXRAD data. An ASR-9 datum must be at least VIP level 2 to be scored. (According to the ITWS Users' Working Group, level 1 precipitation is not considered operationally significant. In addition, the NEXRAD radar is so sensitive that clear air returns of 20 dBZ [well in excess of the level 1 editing parameter] are common. Thus, level 1 AP is often confirmed by NEXRAD clear air returns.) If the NEXRAD data contain no valid weather returns, a flag is set such that the automatic scoring software recognizes that all ASR-9 returns should be removed.

If weather is present in the NEXRAD data, visual comparisons of the ASR-9 and NEXRAD data (before and after the ASR-9 data) are performed. Any returns in the ASR-9 data that do not correspond to valid weather returns in the NEXRAD data, either in location or intensity, are assumed to be AP. Polygons are drawn around those areas. These polygons are entered into a file, along with flags indicating a) that the truther is unsure if the polygon contains AP, b) that the polygon contains AP but the truther is unsure of the correct value of the weather, or c) that the polygon contains AP and what the correct weather level should be. Truth is generated for ASR-9 scans that are about 90 seconds apart (about every third ASR-9 update).

The performance metrics for the AP-edit algorithm are PEAP (probability of editing AP) and PEW (probability of editing weather). PEAP is given by the number of AP pixels correctly edited divided by the total number of AP pixels. PEW is given by the number of weather pixels edited divided by the total number of weather pixels, so the goal is a high PEAP and a low PEW. These statistics are further categorized by the level of the return (*e.g.*, level 3 and greater, level 2 and greater). The minimum operational performance requirements (MOPR) for the AP-edit algorithm are:

1. Edit AP that exceeds the actual weather level by 2 or more levels. Level 1 and 2 AP will be edited when clear air conditions exist over the terminal area.

2. 70% of the AP of at least level 3 will be edited (*i.e.*, PEAP ≥ 70%) when the actual weather reflectivity is ≤ 18 dBZ and the spatial extent of the AP exceeds 25 km^2.

3. 90% of the AP of at least level 2 will be edited (*i.e.*, PEAP ≥ 90%) during clear air conditions when the spatial extent of the AP exceeds 50 km^2.

4. No more than the greater of 10% or 10 km^2 of real weather of at least VIP level 3 will be edited (*i.e.*, PEW ≤ 10%).

Table 2 provides the results of the performance analysis for 9 days in Memphis (6 hours from 3 all-AP days, 8 hours from 3 all-weather days, and 4 hours from 3 mixed

Table 2. PEAP and PEW for all-AP, all-weather, and mixed AP and weather cases.

		All AP	All Wx	Mixed
PEAP (%)	≥ level 2	0.97	-	0.80
	≥ level 3	0.98	-	0.91
PEW (%)	≥ level 2	-	0.00	0.01
	≥ level 3	-	0.00	0.00

days). These data represent on the order of 10^4 pixels of weather and 10^7 pixels of AP. The overall performance for these cases significantly exceeds the MOPR for all categories, although this may not be true on a scan-by-scan basis. Scan-by-scan, the only real concern is not to exceed the 10% PEW requirement. Although this has not happened to date, any such occurrences will be closely investigated.

One would expect that the all-AP days would have a PEAP of 1.0. When the all-AP condition is identified, the ASR-9 scan is "wiped clean". The ability to identify the all-AP condition is directly tied to the quality of the NEXRAD data. It is assumed that comprefl is free of ground clutter and AP contamination. Experience in Memphis has shown that this is seldom the case. The comprefl on a clear-air day then doesn't pass the no-weather test and the AP-edit algorithm is forced into the more conservative pixel-by-pixel edit. ASR-9 AP will be confirmed as real weather based on NEXRAD ground clutter and AP, with a resulting decrease in PEAP.

The AP mask is created at the NEXRAD update rate. If the ASR-9 scan used to create the AP mask is from the middle of the NEXRAD 6-minute volume scan, the AP mask is 3 minutes old relative to the first ASR-9 scan to which it is applied and 9 minutes older than the last application. Evolution of AP (and weather) for that 3 minutes is not represented in the AP mask. As the AP mask ages, the ability to edit AP decreases. This is exemplified in Figure 2.

The data in Figure 2 are from 2300 to 2330 UT 17 July 1994 in Memphis (a mixed case). The vertical lines indicate the times of new AP masks. Generally, the highest PEAP values are found when the AP mask is first applied to the ASR-9 data, when the AP mask is newest. As the AP mask ages relative to the ASR-9 data, performance drops because AP continues to evolve, making the AP mask less representative of the situation. (The total number of AP pixels of ≥ level 3 was on the order of 2000; for ≥ level 2, the total number was around 4000.) This trend is more pronounced when the level 2 AP is included in the analysis. It is interesting to note that over the time period, overall performance improves because the AP intensified but did not develop beyond the original AP area.

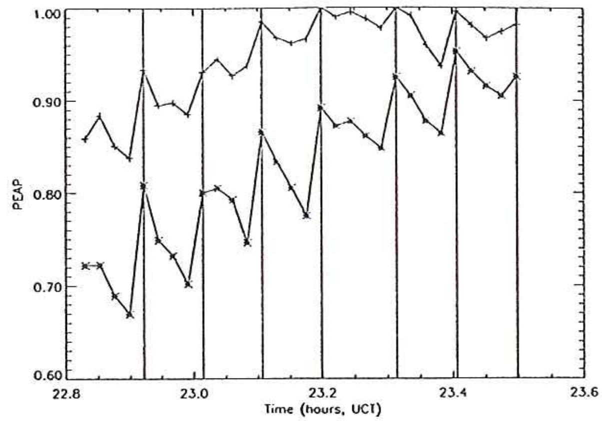

Figure 2. Time series of PEAP for level 2 and greater (*) and level 3 and greater (+) AP.

7. Comments

Because of the spatial smoothing performed by the ASR-9 radar, the ASR-9 weather is "smeared" relative to NEXRAD. Sometimes the leading edges of ASR-9 storms are incorrectly identified as AP and some leading-edge pixels are edited. This condition is usually quickly corrected by the storm motion compensation step, but such errors are reflected in the performance statistics. Throughout the OT&E, the AP-edit algorithm used the 1-km NEXRAD comprefl product. In the fielded Initial Operational Capability (IOC) ITWS, the 4-km comprefl product will be used. The decreased resolution in the NEXRAD data effectively "smears" the weather returns, which may alleviate the problem of editing leading-edge pixels.

It has long been recognized that weather radars are susceptible to AP contamination, therefore one might (quite appropriately) question the assumption that the NEXRAD data are free of AP. In the case of two radars scanning the same area from different locations, even though the sources of the AP returns (ground, buildings, *etc.*) are the same, if the radars are widely separated (for example, the NEXRAD in Melbourne, FL and the ASR-9 at Orlando International Airport) it is unlikely that they will "see" AP in the same locations. The environmental conditions affecting each radar, and therefore the propagation paths of the beams, are different. The likelihood of confirming ASR-9 AP as weather based on NEXRAD AP is slim. On the other hand, two radars that are in close proximity (such as the NEXRAD and ASR-9 at Memphis) will experience the same propagation conditions and can illuminate the same ground targets. In this case, ASR-9 AP will be confirmed as weather by NERXRAD AP.

Since AP cannot be removed from an operational ASR-9, it is essential that AP be removed from the NEXRAD data. This could be accomplished by implementing the technique described by Weber, *et. al* (1993) on a scan-by-scan basis. In addition, use could be made of the fact that AP has no vertical continuity; it is only present on the lowest one or two tilts. A vertical continuity check could be implemented into the algorithm that creates the composite products.

8. Conclusions and Future Work

This paper has described a technique to remove AP from ASR-9 data using the NEXRAD composite reflectivity product. A pixel-by-pixel comparison of NEXRAD and ASR-9 data is performed to identify the presence of AP. Clear-air AP is entirely removed from the ASR-9 data and AP-contaminated weather returns are reduced to the appropriate level. Storm motion is used to reduce the possibility of editing valid weather returns.

The approach used is very conservative to insure that real weather returns are not inadvertently identified as AP and removed. Nonetheless, preliminary scoring results indicate that over 80% of AP is correctly edited from the ASR-9 data. In addition, less than 1% of valid weather returns are edited.

The products that result from the AP-edit algorithm were presented to the Memphis and Orlando users (Tower and TRACON supervisors, Traffic Management Coordinators, and en route supervisors and traffic managers). Questionnaires were distributed to gather feedback on all aspects of the products. The results of those questionnaires were not available at the time this paper was written, but may be presented at the conference.

The AP-removal approach described herein is currently being specified as part of the ITWS IOC. Work to refine the algorithm to make use of multiple ASR-9 radars and multiple pencil-beam radars (*e.g.*, NEXRAD and TDWR) is underway.

9. Acknowledgments

Most of the members of Group 43 Weather Sensing contributed to the development of the AP-edit algorithm in terms of intellectual discussion. However, the authors particularly wish to thank the Memphis and Orlando site personnel (Mark Isaminger, Chris Keohan, Ben Boorman, Durant White, Doug Piercy, Duane Grant, and Stan Dajnak) for their hard work in collecting the data; Mike Donovan, Glenn Perras, and Brian Burns for generating ground truth; and Tim Dasey and Andy Denneno for contributing greatly to the overall algorithm design.

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